Assessing glacial hazards for hydro development in the Himalayas, Hindu Kush and Karakoram

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The catastrophic failure of ice dams formed from surging glaciers in the Hindu Kush-Karakoram, and glacial lake outburst floods from moraine-dammed lakes across the Himalayas can cause enormous damage downstream, including the destruction of hydropower installations. How glacial hazards form and how they are assessed are described in this paper, which also presents the latest multi-criteria analysis method to help rank the degree of hazards using objective criteria. A brief strategy for how glacial hazards might be considered in relation to hydropower development is also presented.

It has been widely reported in the media that the glaciers of the Himalayas are shrinking, which is manifest in prevalent glacier retreat, while those in the Karakoram are stable or flourishing. Changes in the glaciers across the region impact on water resources, hydropower development and tourism, and affect mountain hazards. Of increasing interest in recent years has been the issue of glacial hazards, such as ice dam failures or more specifically, glacial lake outburst floods (GLOFs), which can cause widespread devastation downstream and may pose a significant threat to hydropower schemes. In 1985, the Dig Tsho hydropower scheme in Nepal was destroyed two weeks before its inauguration by a GLOF from an upstream glacial lake. Given the demand for power generation in the region and the significant planned capacity for hydropower over the next decade, this issue merits greater attention than it has received hitherto.

This article provides a brief overview of glacial hazards and their assessment, and provides a strategy for how they might be considered in relation to hydropower development.

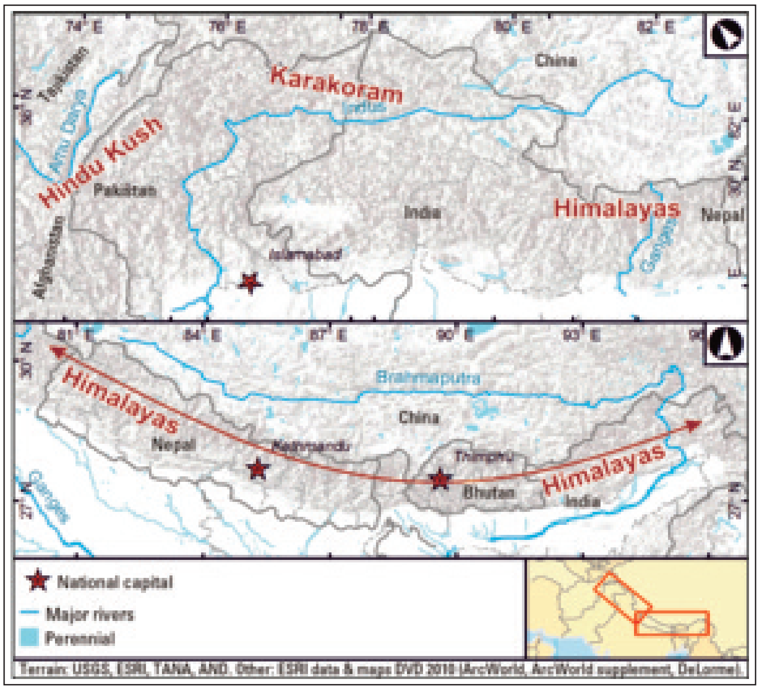


Fig. 1. Locations of the Hindu Kush, Karakoram and Himalayan mountain ranges across Pakistan, Indian, Nepal and Bhutan.

1. Climate change and glaciers

There are two main climatic systems that affect the glaciers across the Hindu Kush, Karakoram and Himalayan region (Fig. 1). The Hindu Kush and Karakoram mountains are dominated by mid-latitude westerly wind systems, which have strengthened in recent decades, resulting in more snowfall [Mölg *et al*., 2014[1]]. The glaciers in this area are stable if not flourishing and advancing [Bolch *et al*., 2012[2]]; and especially those in the Karakoram are showing surging behaviour [Rankl *et al*., 2013[3]]. Surging glaciers undergo periods of accelerated ice flow speeds that can lead to a rapid advance of the glacier terminus, marked changes to the glaciers' surface morphology and topography, and to the distribution of water within the glacier system. Processes relating to glacier surges are as yet still not properly understood. A surging glacier may advance into and block a downstream valley, resulting in the rapid ponding of water and formation of a large volume (multiple cubic kilometres) of water behind an ice dam. Historic failures of such ice dams in the Karakoram in the early 20th century have resulted in massive floods (2 to 3 km^3) with run-out distances in excess of 1200 km.

In contrast, the Indian summer monsoon, which dominates the south side of the Himalayas, has weakened and lengthened, which has resulted in less snowfall to nourish the glaciers. Himalayan glaciers are undergoing significant shrinkage, both by area and volume. This has serious consequences for glacial melt and river flow, and on the use of this water by communities and hydropower schemes. Put more broadly, there is a high confidence that global glacier volumes will continue to diminish by at least 15-55 per cent by the end of the 21st century [IPCC, 2013[4]]. Similarly, Northern Hemisphere spring snow cover is projected to decrease by between at least 7 and 25 per cent over the same time period. There is also high confidence that permafrost temperatures have increased in most regions since the early 1980s [IPCC, 2013[4]]. While this relates predominantly to the high latitudes, especially the Arctic, there is empirical evidence that permafrost at altitude, in places like the Andes, European Alps and Himalayas, is also being affected by rising temperatures. The consequences are being seen as increased high-altitude rock and ice avalanches. Furthermore, high-altitude glaciers appear to be 'cold-based', which means they are well below their pressure melting point, are frozen to their base, and lose mass predominantly through sublimation. Those at lower altitude are either: 'temperate', that is, they are at the pressure melting point, are not frozen to their base, and lose mass predominantly through melting; or, 'polythermal' (higher-altitude parts cold-based, lower-altitude parts temperate).

One of the manifestations of this increasing glacial recession across the Himalayas is the consequential growth in glacial lakes. As a glacier retreats from its terminal moraine formed at the time of its glacial maximum position, water collects behind it and forms a lake. When the restraining dam fails, for reasons explained later, a GLOF is initiated. One such outburst of about 18 × 10^6 m^3 from Luggye Tso in northern Bhutan in 1994 resulted in 21 deaths and widespread damage downstream; the flood wave still had an amplitude in excess of 2 m when it crossed the international border between Bhutan and India, a distance of more than 200 km from the flood's source.

2. Glacial lake formation and associated hazards

An overview of glacial hazards in the Himalayas has been provided by Richardson and Reynolds [2000[5]].

Some of the main hazards associated with glaciers in high mountain areas and their impacts downstream are shown in Fig. 2 [RGSL, 2003[6]]. These are:

(a) A glacial lake.
(b) A low-angle debris-covered glacier tongue on the threshold for formation of a glacier-wide lake.
(c) Ice avalanches, transforming into debris flows.
(d) Failure of saturated glacial sediments becoming debris flows.
(e) Catastrophic rock avalanches (sturzstroms), the most destructive type of landslide, triggered by earthquakes or melting permafrost in glacier head walls.

Other features (shown in Fig. 2) include:

(1) Glacier slab failure and (2) serac collapse, each causing an ice avalanche.
(3) A rock avalanche (possibly in combination with the two features above).
(4) Ice cliff calving, which generates a displacement wave that might propagate to the terminal moraine (M). Following failure of the moraine dam, the ensuing GLOF travels downstream, (5) ricochet ing around the outside of river meanders.
(6) Denudation of the lower parts of the adjacent hill slopes, including the removal of mature forest.
(7) Scouring away of the toes of unstable valley flanks, which can lead to further mass movement (landslides, debris flows, slumps, and so on) contributing sediment load to the flood wave, and to destabilization of the hill slopes.

In the case of surging glaciers, impounded reservoirs form when an advancing glacier tongue flows across and blocks a river valley. Given the flow rates of many rivers in the Karakoram, it takes a relatively short time to build up a significant volume of water, perhaps of the order of days to a few weeks. Once the dammed water level rises enough, the water pressure may become sufficient to jack up the ice dam hydraulically, thereby releasing water sub-glacially, which may in turn lead to the disintegration of the dam and the further catastrophic release of the stored water downstream.

The four Lunana lakes of northern Bhutan (see Fig. 3) serve as useful examples of different glacier and lake system types.

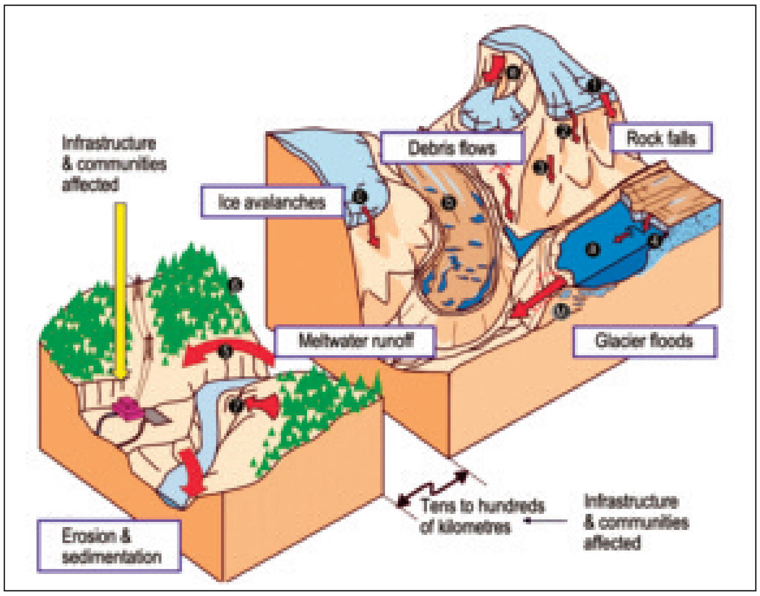


Fig. 2. Schematic illustration of components of glacial hazards. See text for details of the features labelled with numbers and letters.

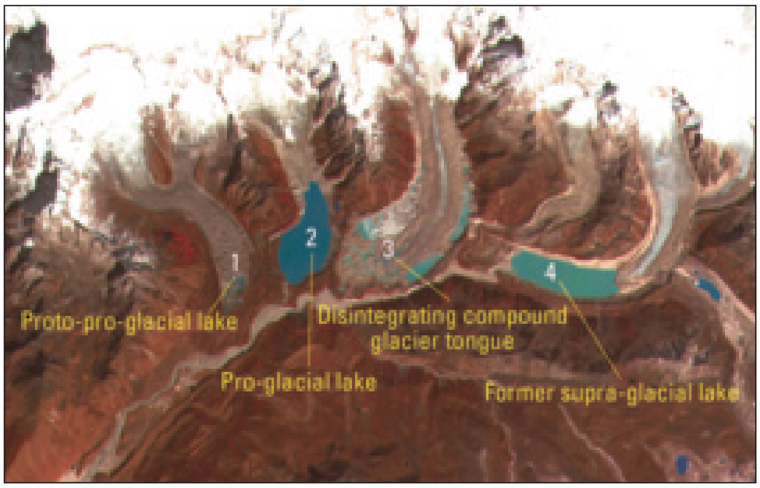
Bechung glacier (1) is a debris-covered valley glacier tongue that has formed by the coalescence of two separate glaciers, each with its own accumulation area; the lowermost part of the snout has a number of discrete supra-glacial ponds that are combining to form a proto-pro-glacial lake.

Raphstreng glacier (2) is a steep valley glacier that terminates in a well developed pro-glacial lake, which has formed behind its terminal moraine.

Thorthormi glacier (3) is, like the Bechung glacier, a compound debris-covered valley glacier that comprises a number of separate flow units which, in the flattest and lowermost parts, are disintegrating by ice calving and forming icebergs; the glacier tongue appears to be floating in its rapidly developing pro-glacial lake.

Luggye glacier (4) is a much larger glacier with a steep accumulation zone flowing into a long flat-lying, mostly-stagnant, debris-covered glacier tongue. The accumulation of a thick debris mantle at the downstream end of the glacier has resulted in reduced ablation of the underlying ice and an elevated topography relative to the upstream part of the glacier, restricting drainage from the glacier surface. Many supra-glacial ponds have combined to form one large supra-glacial lake (now called Luggye Tsho) separating the down-

Fig. 3. SPOT satellite image (2002) showing the Lunana Lakes of northern Bhutan. See text for details.



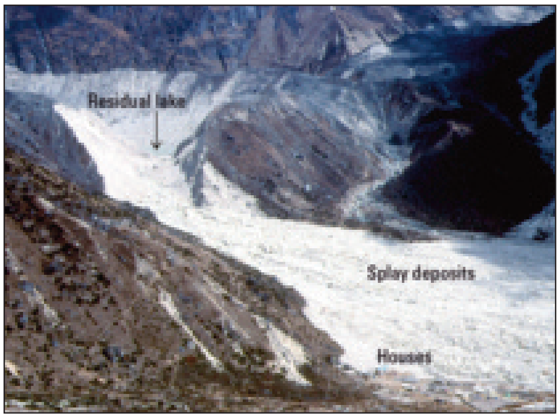


Fig. 4. GLOF breach through the moraine at Tsabai Tsho, Nepal, which occurred in 1998.

stream debris-mantled stagnant ice from the main glacier. In the 2002 SPOT image shown in Fig. 2, the GLOF breach in the left lateral moraine of Luggye Tsho is evident as light coloured sediments, which also reveal the GLOF track downstream to the southwest corner of the image.

When a glacial lake bursts, it forms a large breach through its damming moraine (Fig. 4), with a splay deposit of coarse debris immediately downstream.

From work undertaken in Bhutan [Reynolds, 2000[7]] and detailed monitoring of glacier flow using remote sensing techniques [Quincey *et al*., 2007[8]] it is now well understood how glacial lakes form. For the lowermost parts of glaciers where the net mass balance is negative, the relationships between surface gradient and ice flow characteristics are summarized in Table 1.

A benefit of this <2° criterion for supra-glacial lake development is that it has been possible to establish a remote sensing technique to map areas of glaciers with such shallow surface gradients, hence making it possible to map prospective lake growth [Quincey *et al*., 2007[8]]. For example, Imja glacier could double its current length to 4.4 km length, whereas Lhotse Glacier, also in the Solukhumbu, Nepal, has and will have supra-glacial ponds on its debris-covered surface, but the surface gradient is too steep for any large supra-glacial lake to form. Significantly, the nearby Ngozumpa glacier is forming supra-glacial ponds in the snout area immediately behind its terminal moraine and, with the known extent of the flat-lying part at <2°, could form a lake about 9 km long (with an area of about 6.5 km^2 and a volume of about 330 $\times 10^6$ m^3 depending on the lake depth). The questions become: Does the development of such a large lake represent a significant hazard and/or a significant water resource? And, how should such a lake system be monitored and managed over the coming decades and by whom?

It is important to recognize within the glacier 'system' the range of landforms, possible mass movement processes and other influences from within the glacier system environment, from the top of the high headwall, around the surrounding mountain flanks to the lowest terminal moraine dam. A holistic overview of the glacial system helps to identify key components that, if present, may trigger one or more processes that might lead to the formation of a GLOF.

To this end, the shape and form of an individual lake basin influences how the lake water behaves to an external trigger, such as a rock and ice avalanche. This, in turn, influences processes affecting moraine dam stability, possible breach mechanisms and ultimately, flood characteristics. Three examples of lake water body behaviour are shown in Fig. 5. In the first example (Fig. 5a), the lake basin is approximately semi-circular in longitudinal profile, such that the lake length (L) is around twice the maximum water depth (h). Given the rapid and high energy influx of about 10 per cent by volume of the lake, seiche wave oscillations will be established. The first and perhaps immediate succession of oscillations may overtop the moraine

Table 1: Relationship between glacier surface gradients, ice flow and supra-glacial lake development (modified from Quincey *et al.* [2007[8]] and based on Reynolds [2000[7]]

Surface gradient and ice flow characteristics	Interpretation
Gradient <2°, stagnant ice	Minimal opportunity for reorganisation of drainage conduits, promoting large-scale lake development by the growth and merger of perennial discrete supra-glacial ponds.
Gradient <2°, measurable flow	Many small discrete perennial supra-glacial ponds merge and likely to form a large lake but with a potential for limited drainage through the reorganization of drainage conduits through flow.
Gradient 2-6°, stagnant ice	No opportunity for reorganisation of drainage conduits through flow, but steeper hydraulic gradient aids drainage; major supra-glacial lake development is unlikely although small transient ponds may form.
Gradient 2-6°, measurable flow	Opportunity for reorganisation of drainage conduits through flow and steeper hydraulic gradient aids drainage, resulting in more efficient drainage conditions so that development of a large perennial supra-glacial lake is unlikely; some transient supra-glacial ponds possible.
Gradient 6-10°, measurable flow	Opportunity for reorganisation of drainage conduits through flow and steeper hydraulic gradient aids drainage, resulting in efficient drainage conditions so that development of a large perennial supra-glacial lake is very unlikely; some small, isolated transient supra-glacial ponds possible in lower gradient areas.
Gradient >10°, measurable flow	All melt water is able to drain away through drainage conduits and steep hydraulic gradients; no evidence of ponding.

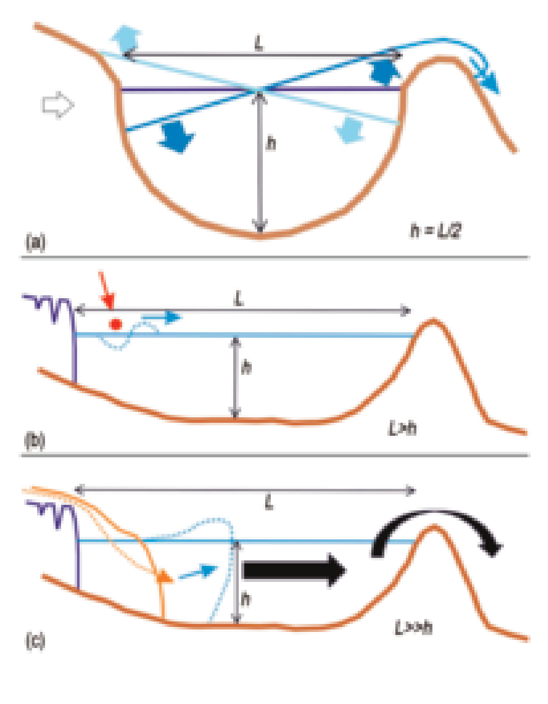


Fig. 5. Schematic illustration of how lake water behaves when influenced by an external trigger.

dam and may lead to its failure and degradation, thereby releasing lake water in a GLOF. The Dig Tsho dam breach of 1985 is known to have been caused by an ice avalanche that established a series of seiche wave oscillations which breached the dam [Westoby *et al*., in press[9]] and resulted in several pulses of flood water, each of which behaved differently over different run-out routes within the main river channel.

The second example (Fig. 5b) is more typical of a long supra-glacial lake, such as Luggye Tsho in Bhutan or Tsho Rolpa in Nepal, where the lake length is significantly greater than the maximum lake depth. In this case, if a small ice calving event occurs at the glacier tongue, constituting say <<1 per cent by lake volume, a 'displacement wave' is generated, the energy from which propagates horizontally through the lake towards the terminal moraine, where it may, if large enough, cause a wave that overtops a low freeboard; alternatively it may just be reflected back towards its source. At Tsho Rolpa in Nepal, for example, ice calving events at the glacier snout generated displacement waves that have been observed to have wave heights of between 0.3 m and more than 2 m at the terminal moraine, more than 3 km from the snout.

The third example (Fig. 5c) consists of a very large influx of debris from a rock avalanche, for instance, with a volume of about 10 per cent of the lake volume, into a long lake where the length is significantly greater than the maximum water depth. The influx of material displaces a sufficient proportion of the lake to form an 'avalanche push wave', which itself propagates horizontally along the length of the lake to the natural dam, where it either overtops a shallow freeboard, or is reflected back into the lake basin and may lead to several horizontal oscillations of the reflected wave.

Moraines can fail from: internal piping, leading to mechanical failure; melting of buried ice within the moraine through thermokarst processes leading to subsidence and then failure; overtopping by a single wave that causes regressive erosion and subsequent failure or by a sequence of overtopping waves until failure is achieved; and, seismically induced failure. Each will generate a different form of breach and a subsequent flood event with a different hydrograph shape, complexity and duration. Assumptions about how a given moraine may fail and the form of the subsequent flood can make a huge difference when it comes to modelling flood behaviour.

A key issue for downstream vulnerability mapping is the modelling of GLOF events. A review of modelling outburst floods from moraine-dammed lakes has been provided by Westoby *et al*. [in press[9]]. The majority of published accounts of reconstructions or predictions of GLOF events have been limited, often by necessity, to the use of models that are too simplistic. The results of such modelling can be widely unrepresentative of what has happened or is likely to happen, and so should be used with caution. Physically based algorithms represent the state-of-the-art in numerical dam-breach modelling, but few have been applied to investigate the characteristics of GLOFs [Westoby *et al*., in press[9]].

3. Assessing glacial hazards

Two issues exist: how to assess glacial hazards across a region in a consistent and meaningful way; and, how to rank them in terms of the severity of the hazard. It is important to recognize that just because a glacial lake may contain a large volume of water, this does not necessarily make it inherently hazardous.

Table 2: Trigger potential and threshold parameters for glacial hazard assessment

	Parameter affecting hazard score*	0	2	10	30	50
1	*Effective volume of lake water available for flood*	N/A	Low	Moderate	Large	Very large
2	*Height of freeboard relative to lake level*	No dam	Very high	High	Moderate	Low
3	*Width/height ratio of terminal moraine dam*	w >> h	w > h	w ≈ h	w < h	w << h
4	*Gradient of distal moraine dam*	Flat-5°	5-10°	10-25°	25-40°	>40°
5	Height of glacier ice cliff and calving potential	No cliff	Low	Moderate	High	Very high
6	Ice/rock avalanche into lake	Open basin	Low	Moderate	High	Very high
7	Thermokarst degradation within terminal moraine	No ice	Low	Moderate	High	Very high
8	Buoyancy of submerged stagnant ice based on possible ice volume	No ice	Low	Moderate	High	Very high

*Threshold parameters are shown in italics.

As most glacierized areas in high-mountain regions are remote, and therefore difficult to visit without significant and expensive logistical effort, remote sensing techniques have come to the fore over the last two decades by which first-pass hazard assessments over large areas (hundreds of km^2) can be undertaken [Quincey *et al*., 2005[10] and 2007[8]; RGSL, 2002[11,12] and 2007[13]]. Very-high-resolution imagery (<1 m ground resolution) and associated digital elevation models can be used for more geographically restricted areas (for example <10 km^2) for more detailed assessments of specific glacial lake systems. The results from such analyses can be used to design field programmes that merit the investment. These may include, for example, detailed geomorphological, geophysical, topographical and engineering geological surveying and mapping, such as described by RGSL [2003[6]] and Hambrey *et al*. [2008[14]].

There are a number of threshold factors that can be used to categorize any given glacial lake system, but which on their own do not designate the existence of any hazard. These are listed in Table 2 [modified from RGSL, 2003[6]]. However, for a hazard to exist, there must be potential for a trigger event to occur that can lead to a possible GLOF. The key factors affecting the likelihood of a GLOF include [modified from RGSL, 2003[6]]:

- minimal moraine freeboard above the lake level with narrow dam width, rendering the dam vulnerable to overtopping;
- evidence of avalanches from valley sides and/or hanging glaciers directly into the lake that might induce either a seiche or avalanche push wave;
- evidence of seepage and/or piping through the moraine dam; and,
- evidence of degradation of an ice core within the terminal moraine dam that might cause progressive collapse.

For both threshold and trigger parameters, there are scale factors that can be used to weight how important

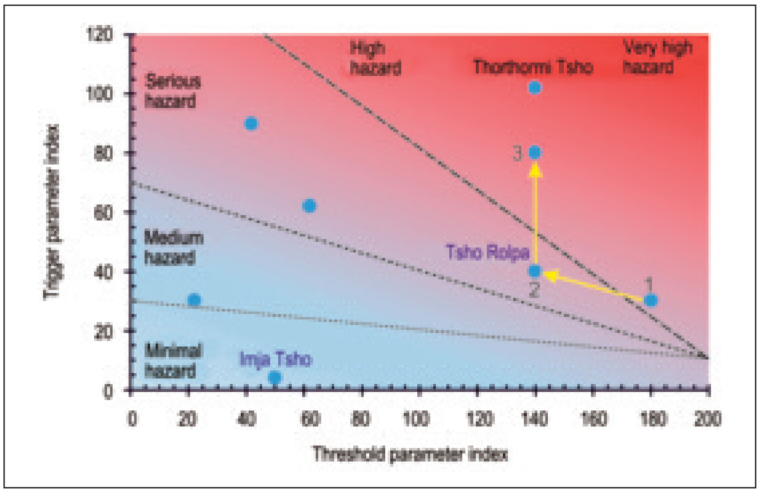


Fig. 6. Example of a Multi-Criteria Analysis hazard ranking graph. Sample scores for a number of glacial lakes are shown including Imja Tsho (Nepal) and Thorthormi Tsho (Bhutan) with three separate rankings for Tsho Rolpa, Nepal: (1) pre-interim remediation (prior to 2000); (2) post-interim remediation (2000); and (2) to (3) showing the increasing hazard associated with the growing issue of melting submerged stagnant ice until it reaches catastrophic buoyancy.

or significant any factor is. This forms part of a Multi-Criteria Analysis that was first developed for use in hydropower projects in Bhutan in 1998, and which has subsequently been developed for use in any glacierized region [RGSL, 2003[6]]. It is beyond the scope of this article to discuss the physical basis for the weighting system. However, the scheme currently in use is listed in Table 3. This enables a hazard score to be derived using the weightings for both threshold and trigger parameters and plotted on a hazard ranking graph (Fig. 6).

4. Monitoring glacial hazards for hydropower projects

There are three strategies to manage glacially derived floods, be they from moraine-dammed lakes or from ice dam failures, namely:

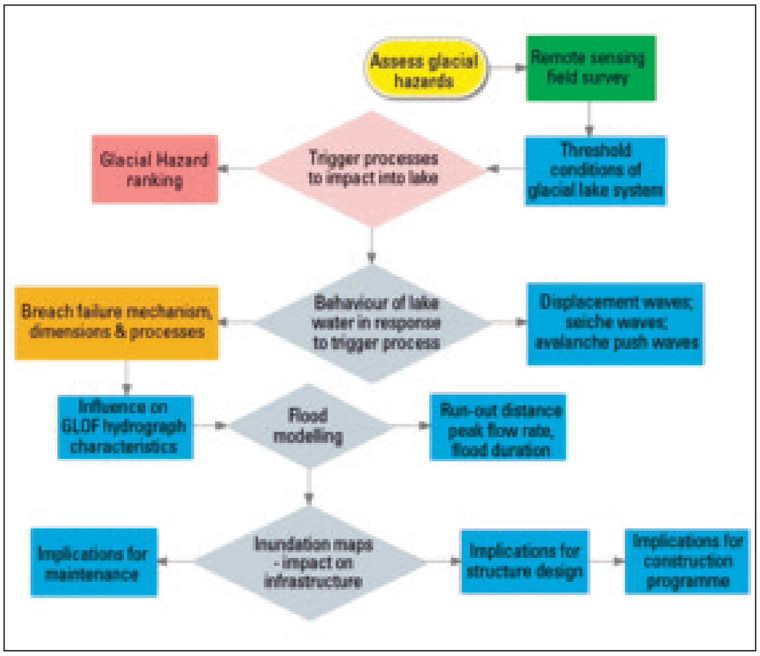


Fig. 7. Simplified flow chart for assessing glacial hazards for hydropower schemes.

(a) resistance;
(b) deflection; and,
(c) avoidance.

In the first case, the design and construction programme of the structures should take into account the range of flood types and magnitudes, and ensure that the structures are capable of resisting such inundation to defined levels of damage. In the second case, the scale of possible flood events may be too large to be able to engineer resistant structures, and it becomes necessary to build structures upstream between the hydropower facility and the flood source, to divert the main flood away from vulnerable or key structures or to dissipate its energy. Such diversion structures might include weirs and diversion dams. The third case is where neither of the first two are practical, and where the only solution is to remove the water from the source, such that a flood never occurs or only occurs with reduced capacity, so that the resulting flood can be dealt with by either (a) or (b) or both. However, each of these scenarios requires that the likely nature of the potential flood has been defined to within acceptable and realistic limits of certainty. To this end, the limitations of GLOF modelling discussed above are germane. It is also important to recognize that, once an assessment of likely flood events has been undertaken before or during the feasibility stage of a hydropower project, the nature of the upstream hazards should be reviewed on a regular basis, as they will change in response to changing climate.

Whereas GLOFs, once they have occurred at a particular glacial lake system, are very unlikely to recur, given that the ponding dam will have been breached, glaciers in the Karakoram, for example, may undergo repeated phases of surging [Quincey and Luckman, 2013[15]]. Therefore, once a glacier has surged, it cannot be assumed that it will not do so again. While the return periods of glacier surges in the Karakoram are almost entirely unknown, the Khurdopin glacier, for example, surged during the late-1970s. The same glacier surged again in the late 1990s, indicating a return period of 20 years [Quincey and Luckman, 2013[15]]. This suggests that if glaciers exhibiting surge-type behaviour are present within the catchment of a hydropower scheme with a design life of 50 years, there is a significant probability that the same glaciers will surge again during that period, perhaps more than once.

To maintain vigilance, it is strongly recommended that the glacial hazards within catchments upstream of any hydropower facility are reviewed systematically and regularly, such as every five years. It is possible that hazards that did not exist during the feasibility study period may develop after construction, and may become more significant with time. An outline scheme for the routine monitoring and assessment of glacial hazards is given in Fig. 7.

5. Conclusions

Increases in global temperatures in view of climate changes being highly likely, coupled with reductions in snow fall, and increased thawing of permafrost, including at high altitude, mean that the style and scale of mountain and, in particular, glacial hazards are also likely to change over time. Many glaciers in the Himalayas, from northwest India through Nepal, Sikkim to the east of Bhutan, are retreating significantly, with some in states of disintegration. This recession is coupled with increasing volumes of melt water being stored as glacial lakes, dammed behind moraines. When such a glacial lake system reaches a critical point of marginal stability, an external trigger, such as a rock/ice avalanche, sudden influx of water from an upstream glacial lake, or potentially an earthquake, can cause the moraine dam to fail, thereby releasing increasingly large volumes of water as outburst floods. Runout distances of more than 200 km for Himalayan GLOFs and more than 1200 km for outbursts from ice dam collapses in the Upper Indus catchment have been reported.

Given the significant existing and planned capacity for hydropower in the Hindu Kush, Karakoram and Himalayas, it is recommended that the glacial hazards in upstream catchments are properly assessed and then reviewed and monitored regularly, preferably every five years. ◊

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J.M. Reynolds

Prof John M. Reynolds holds a BSc in Geological Geophysics (from Reading University, UK) and a PhD in Glacio-geophysics (from CNAA, Reading University and British Antarctic Survey, Cambridge, UK). He has held posts at the British Antarctic Survey (Cambridge), Plymouth Polytechnic (now Plymouth University), and has run his own geological and geophysical consultancy practice, of which he is Managing Director, since 1994. He was appointed as an Honorary Professor at Aberystwyth University, UK, in 2005. He is currently a Member of the Advisory Board of the Glacier and Permafrost Hazards in Mountains (GAPHAZ) Standing Group of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). He first became involved with glacial hazards in Norway in 1976. Subsequently he has worked: on developing protocols for the assessment of glacial hazards (funded by the Department for International Development); on glacial hazard assessments for the whole of Bhutan as part of the Hydropower Master Plan for Bhutan (with Norconsult, Norway); as International Technical Adviser to the Government of Nepal on glacial hazards; and on a wide range of other glacial hazard projects in Nepal, Bhutan, Pakistan, and Kyrgyzstan; he has also reviewed projects in Tajikistan, as well as developed projects for the Indian Government for remote mapping of Himalayan glaciers using helicopter-borne sensors. He guided the installation of the first engineered remediation of a glacial lake in the Himalayas in Nepal (1995-2000) and the first Early Warning System (1999). He pioneered the use of geophysical investigations for glacial hazard assessments in the Himalayas (1996). In addition, he has worked extensively in Peru and Chile on a range of glacial hazards projects for the civil defence, hydropower and mining sectors since 1988. He has also directed a number of geophysical consultancy projects for hydropower dam foundation studies in Georgia and Zambia.

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